

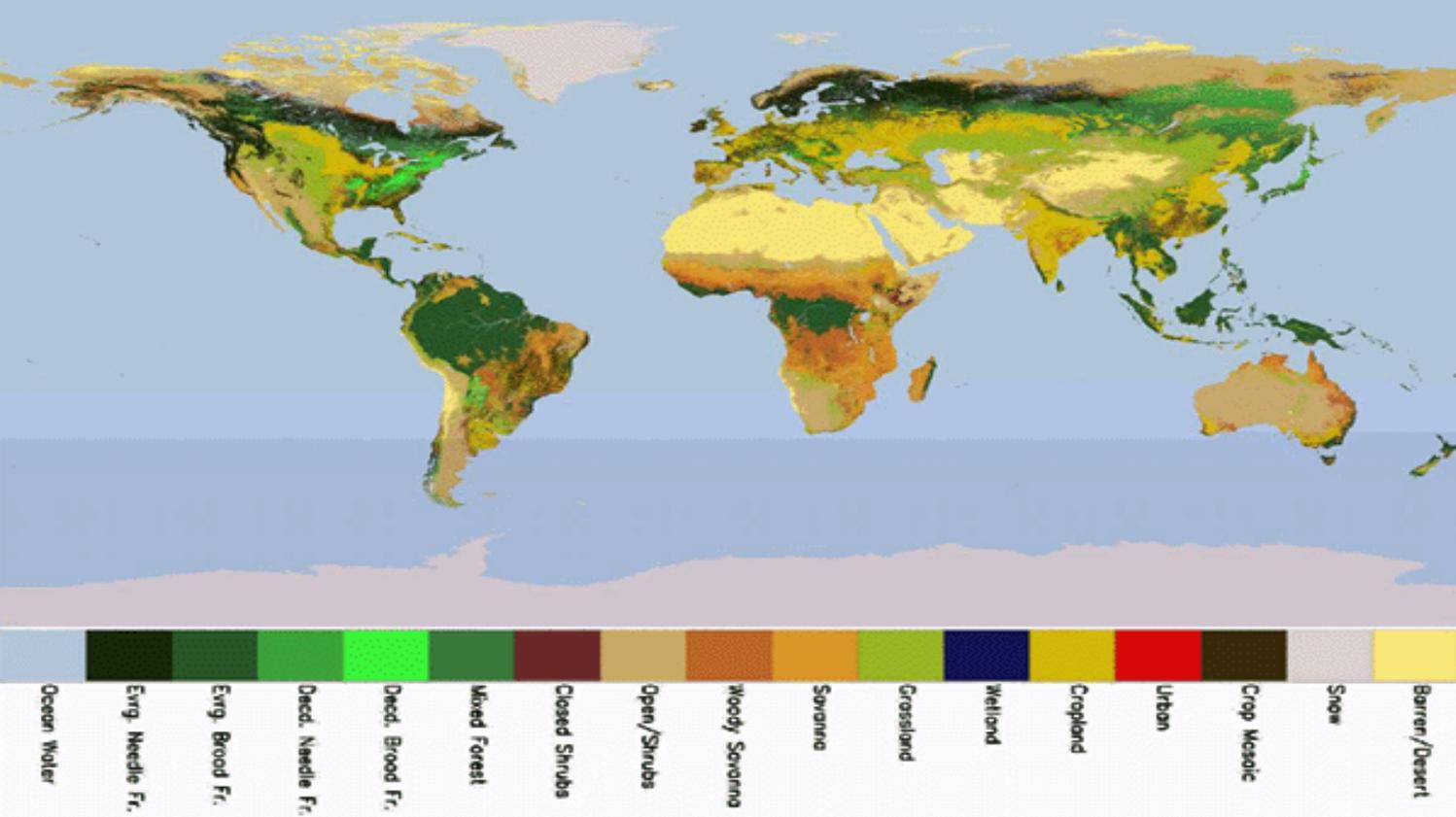


# **Modeling Polarization Properties of Reflected Solar Spectra from Evergreen Broad-Leaf Trees**

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## **Introduction**

- **Broad-leaf-forest-reflected solar radiation's degree of polarization (DOP) can be as large as ~70%, according to PARASOL data.**
- **To correct polarization-induced error in satellite data, polarization state of solar spectra from broad-leaf trees must be obtained.**
- **However, empirical PDMs from PARASOL data can be obtained only at 3 wavelengths, i.e. 490, 670, and 865 nm.**
- **Polarization properties of solar spectra from evergreen broad-leaf trees are modeled with ADRTM and PARASOL data in this work.**



Evergreen broad-leaf trees are mostly in low latitude.

## Scene types for which we have developed models:

- Ocean and other water bodies.
- Desert/bare land
- Evergreen needle-leaf trees



## Theory for modeling polarized RS from broad-leaf trees



The problem for reflected solar radiation modeling is focused on obtaining surface reflection matrix for the different scene types

$$\mathbf{R}(\theta_s, \theta_v, \varphi) = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ R_{41} & R_{42} & R_{43} & R_{44} \end{bmatrix} = \mathbf{R}_1(\theta_s, \theta_v, \varphi) + \mathbf{R}_2(\theta_s, \theta_v, \varphi)$$

$$\mathbf{R}_1(\theta_s, \theta_v, \varphi) = \begin{bmatrix} R_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} C_1 R_{leaf} + (1 - C_1) R_{soil} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$R_{leaf}$   $R_{soil}$  are from PROSAIL model for leaves spectra

All other elements of  $\mathbf{R}$  are from



$$\mathbf{R}_2(\theta_s, \theta_v, \varphi) = \begin{bmatrix} 0 & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ R_{41} & R_{42} & R_{43} & R_{44} \end{bmatrix} = C_1 C_2 \left[ C_3 \frac{\pi \mathbf{M}(\theta_s, \theta_v, \varphi)}{4 \cos^4 \beta \cos \theta_s \cos \theta_v} P_1(Z_x, Z_y) + (1 - C_3) \frac{\pi \mathbf{M}(\theta_s, \theta_v, \varphi)}{4 \cos^4(\beta - \pi/2) \cos \theta_s \cos \theta_v} P_2(Z_x, Z_y) \right]$$

$$P_1(Z_x, Z_y) = \frac{1}{\pi \sigma^2} \exp\left(-\frac{Z_x^2 + Z_y^2}{\sigma^2}\right) = \frac{1}{\pi \sigma^2} \exp\left(-\frac{\tan^2 \beta}{\sigma^2}\right)$$

$$P_2(Z_x, Z_y) = \frac{1}{\pi \sigma^2} \exp\left(-\frac{Z_x^2 + Z_y^2}{\sigma^2}\right) = \frac{1}{\pi \sigma^2} \exp\left[-\frac{\tan^2(\beta - \pi/2)}{\sigma^2}\right]$$

$$Z_x = \frac{\sin \theta_v \cos \varphi - \sin \theta_s}{\cos \theta_v + \cos \theta_s} \quad Z_y = \frac{\sin \theta_v \sin \varphi}{\cos \theta_v + \cos \theta_s} \quad \tan \beta = \sqrt{Z_x^2 + Z_y^2}$$

$C_1$   $C_2$   $C_3$   $\sigma$  are from fitting the modeling results to PARASOL data at 490, 670, and 865 nm.

$c_1$  = tree fraction

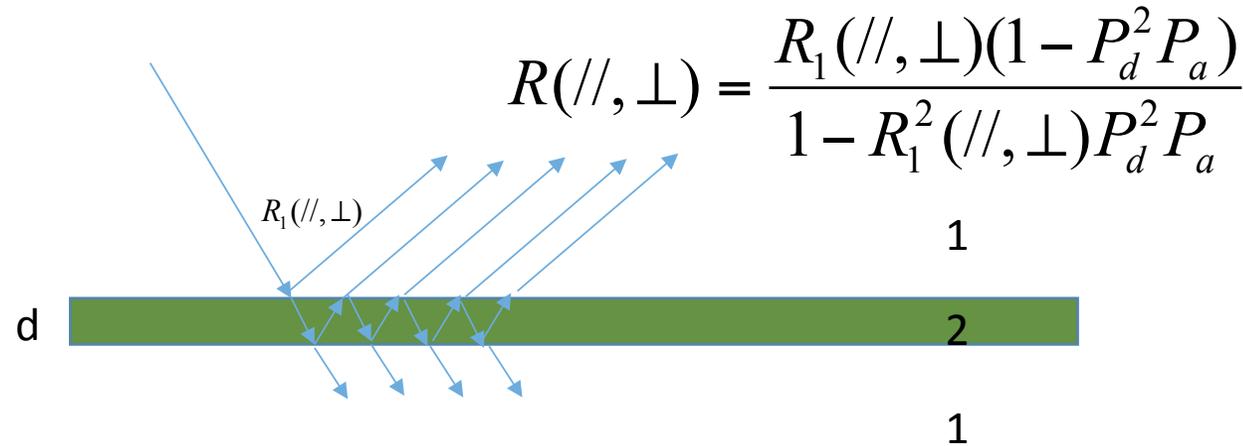
$c_2$  = specular reflection leaf fraction

$c_3$  = fraction of leaves preferably horizontal.

$\mathbf{M}(\theta_s, \theta_v, \varphi)$  4x4 elements are from specular reflection matrix elements of leaves  $\mathbf{R}_s$ .



Specular reflection matrix of leaves is calculated from a lossless dielectric slab



$$P_a = \exp(i2k_1 d \tan \theta_t \sin \theta_i)$$

$$P_d = \exp(ik_2 d / \cos \theta_t)$$

With  $R(//, \perp)$  we can calculate the reflection matrix of the leaf slabs  $\mathbf{R}_s$ .



## Leaf and soil spectral reflectance from PROSAIL (Jacquemoud et al. 2009)

### *Erectophile leaves*

<i>Cab</i>	=	20.0	<i>Chlorophyll content (<math>\mu\text{g.cm}^{-2}</math>)</i>
<i>Car</i>	=	10.0	<i>Carotenoid content (<math>\mu\text{g.cm}^{-2}</math>)</i>
<i>Cbrown</i>	=	1.0	<i>Brown pigment content (arbitrary units)</i>
<i>Cw</i>	=	0.015	<i>EWT (cm)</i>
<i>Cm</i>	=	0.009	<i>LMA (<math>\text{g.cm}^{-2}</math>)</i>
<i>N</i>	=	1.2	<i>Structure coefficient</i>
<i>Psoil</i>	=	0	<i>Wet soil</i>
<i>LAI</i>	=	8.0	<i>Leaf area index (<math>\text{m}^2/\text{m}^2</math>)</i>

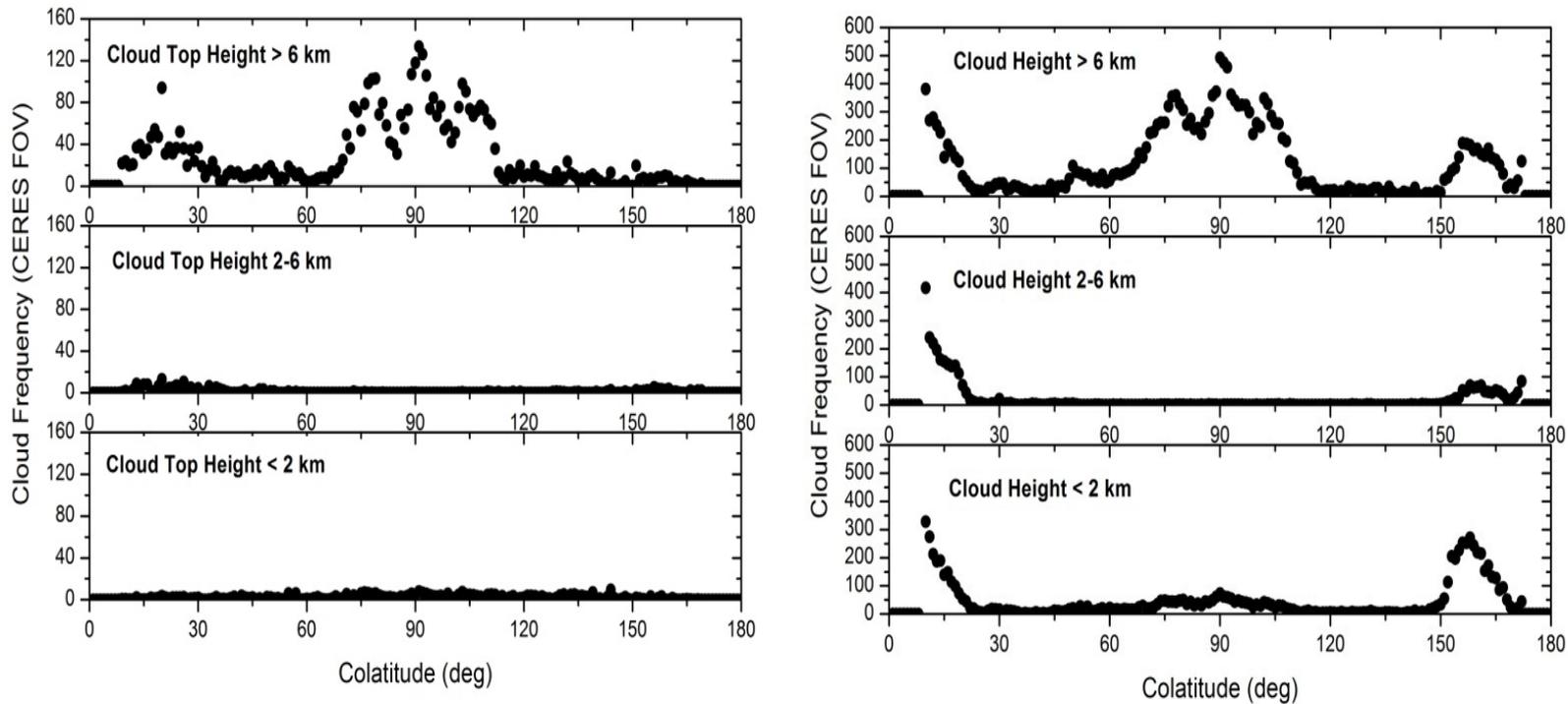
$$c_1 = 0.6 \quad c_2 = 0.6 \quad c_3 = 0.05$$

$$\sigma = 0.0207$$

$$\tau^a(\lambda) = \beta \cdot \lambda^{-\alpha}$$

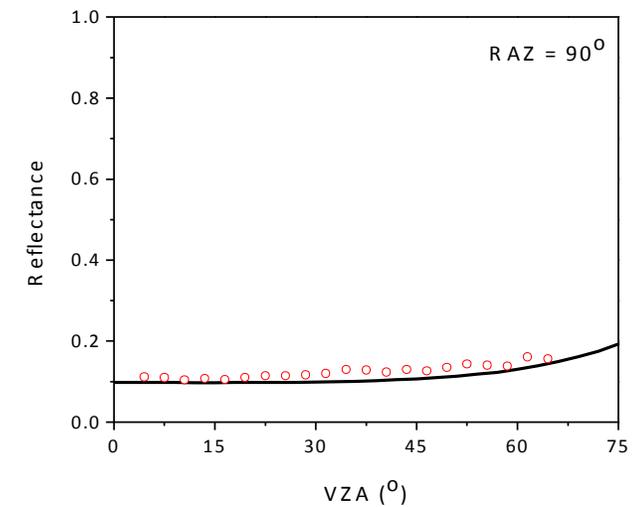
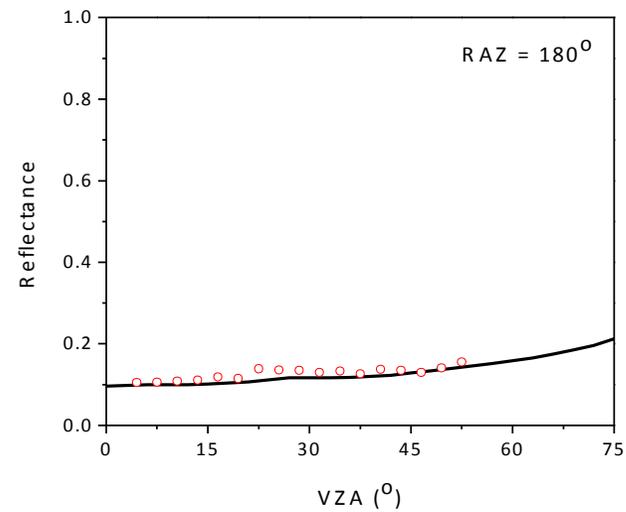
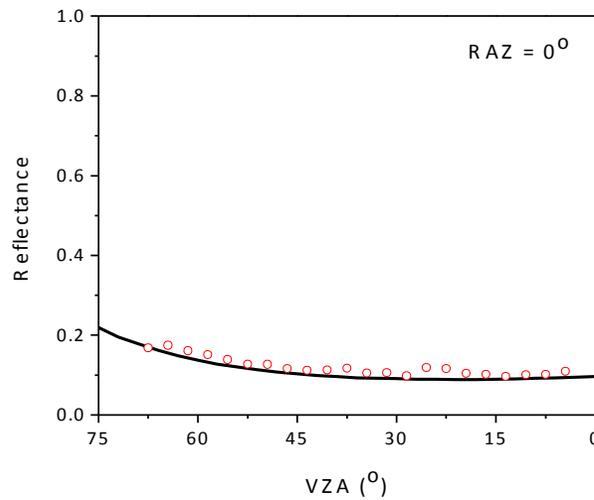
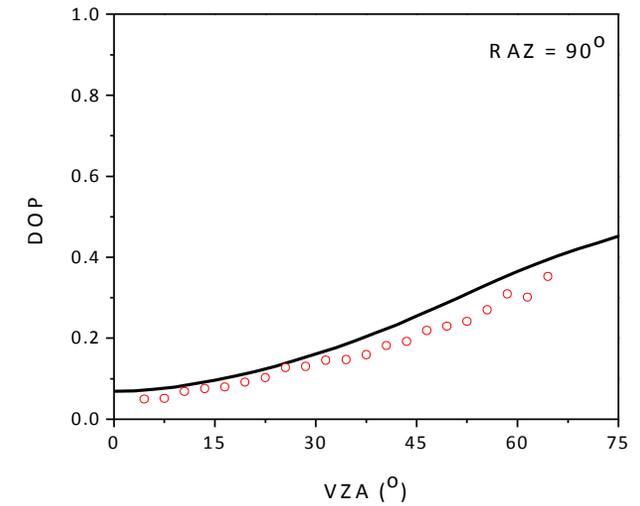
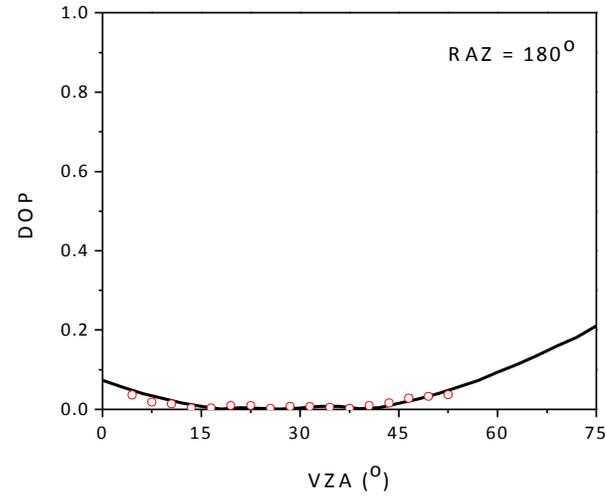
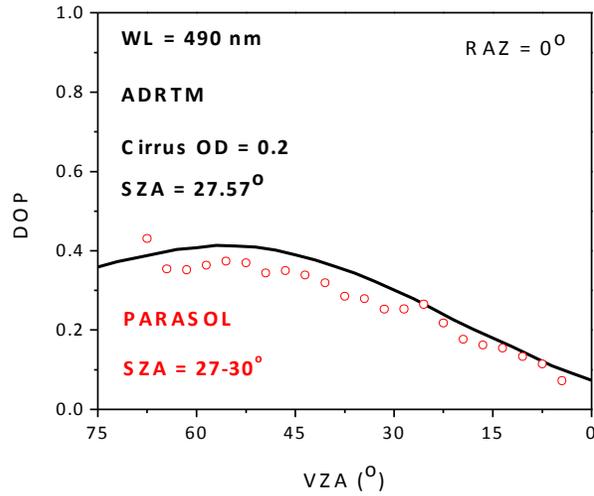
Aerosol turbidity number  $\beta = 0.045$  and Angstrom number  $\alpha=1.55$  for forest in Western Siberia (Sakerin and Kabanov, 2006)

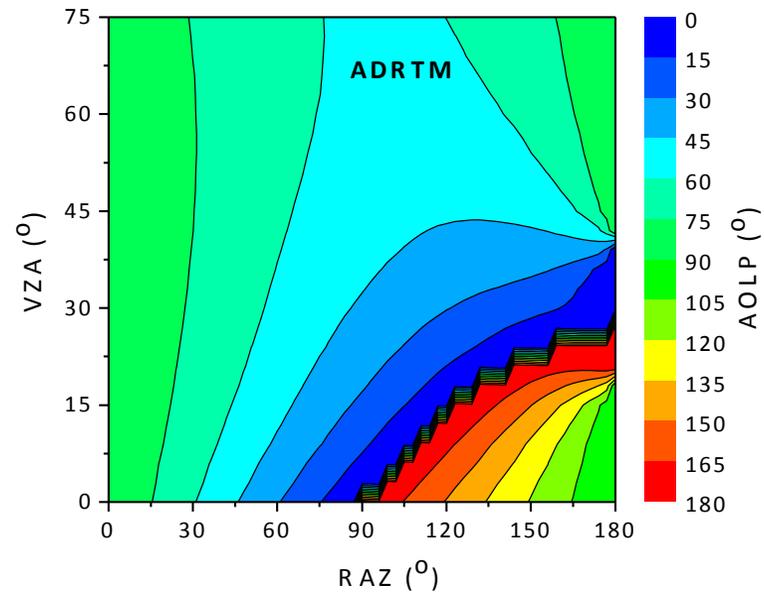
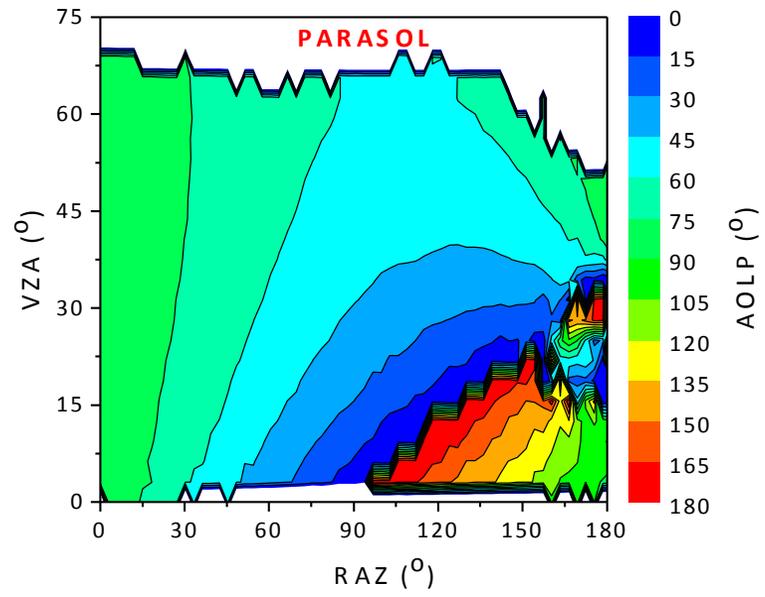
For modeling polarization of solar reflection at low latitude, we must consider super-thin cloud with  $OD < \sim 0.3$  which cannot be detected by current passive sensors such as the MODIS.



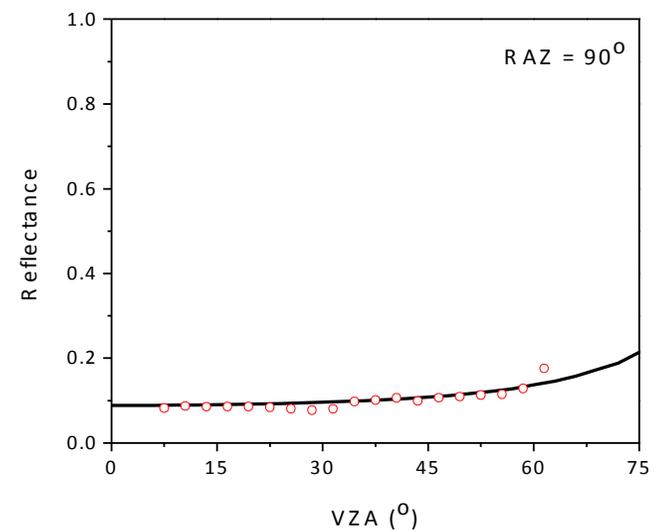
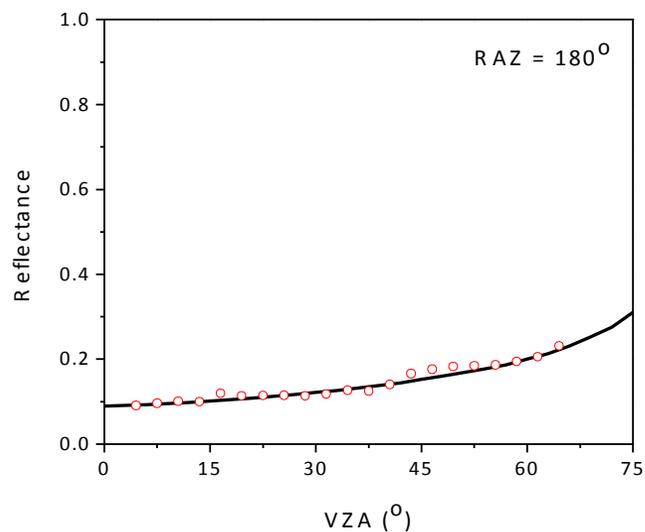
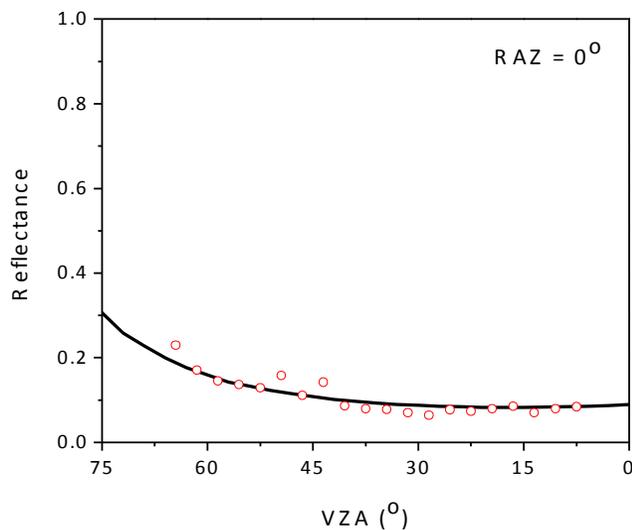
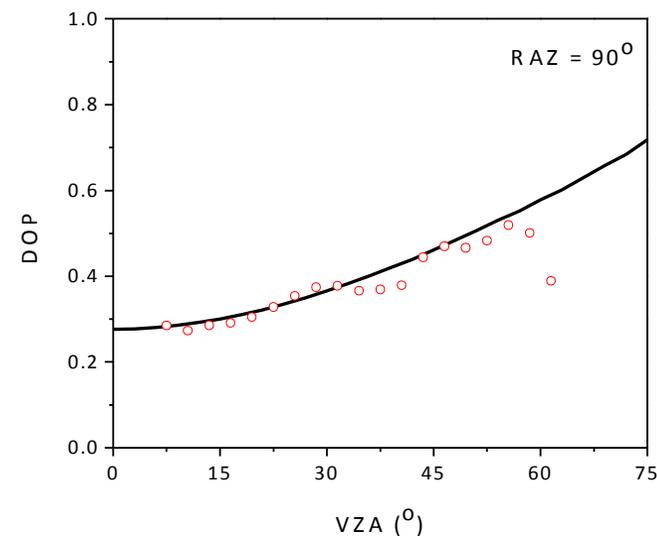
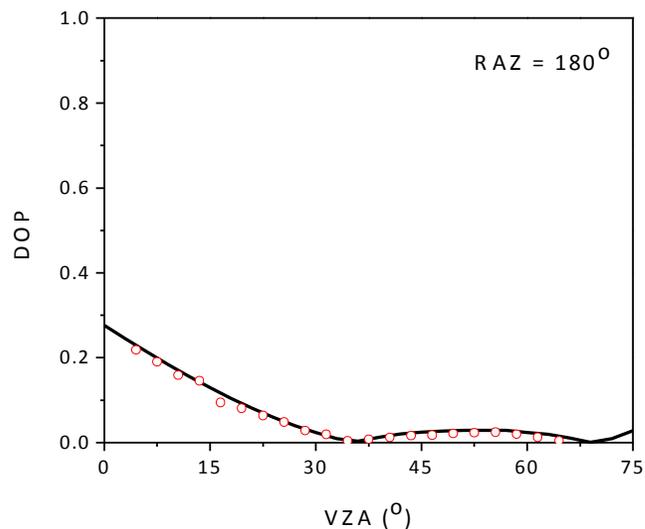
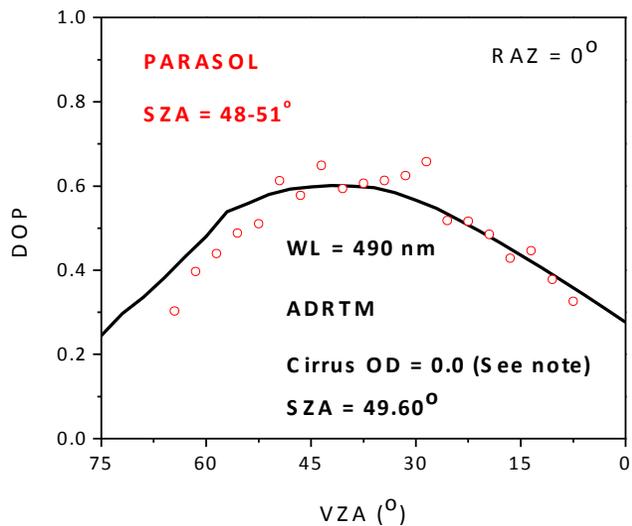
**Zonal and altitude distribution of invisible cloud occurrence frequency (in the unit of CERES FOV number) for daytime (left panel) and nighttime (right panel) ocean**

# Comparing model results with satellite data at a wavelength of 490 nm and a SZA of 27.57 deg

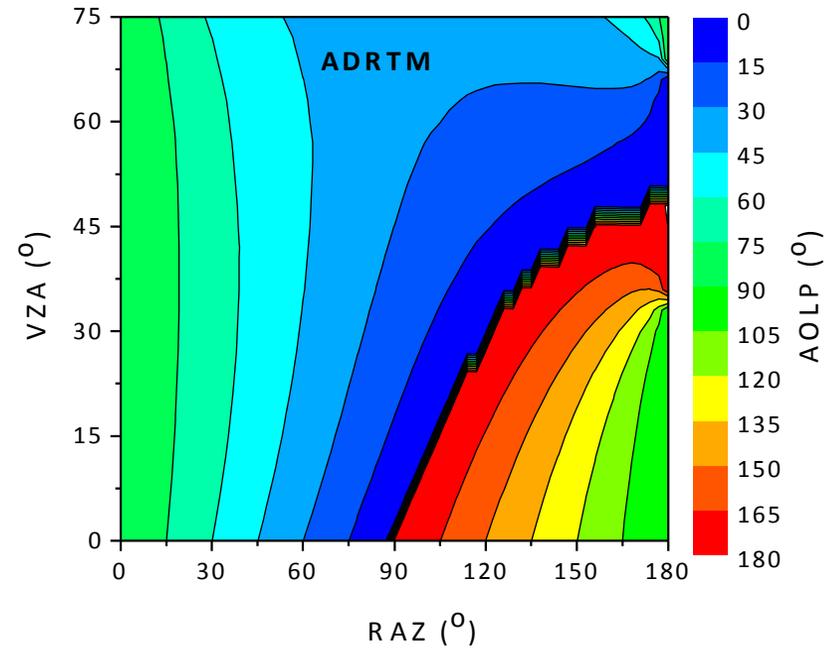
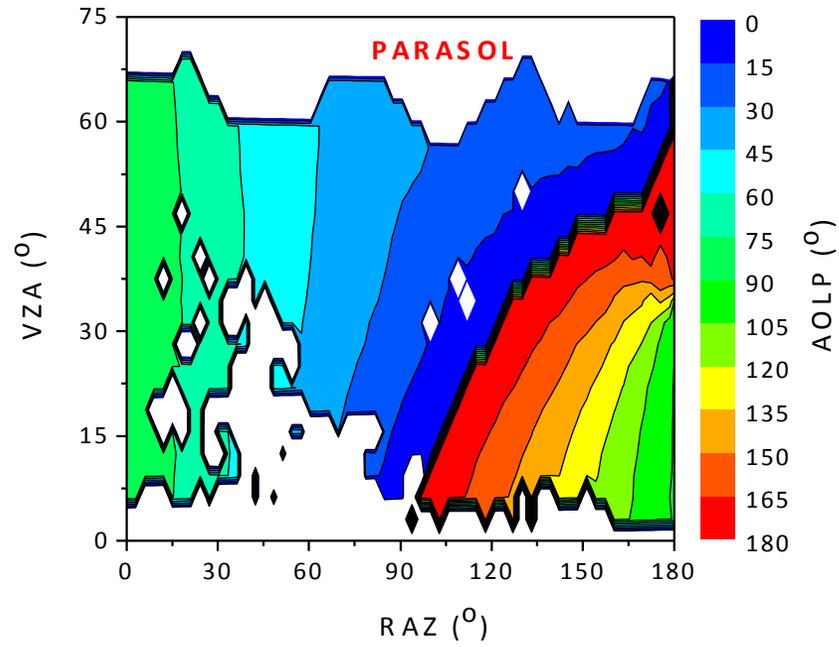




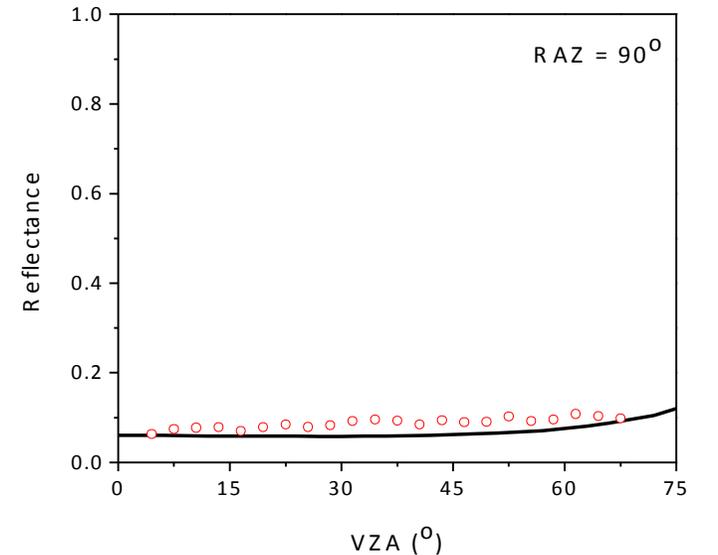
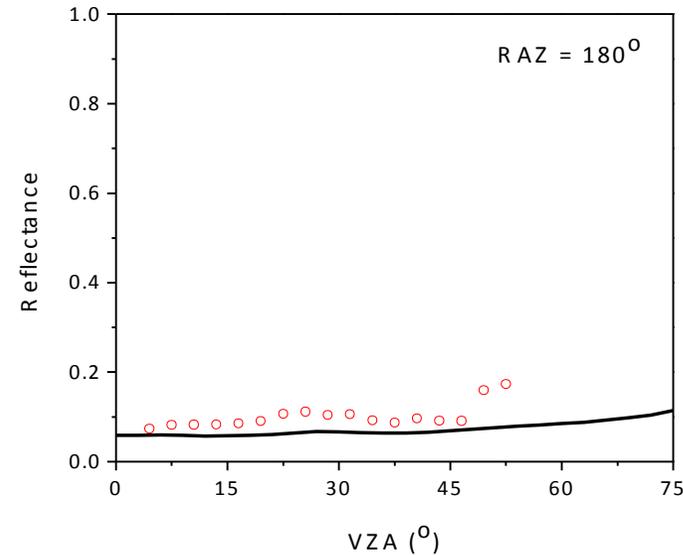
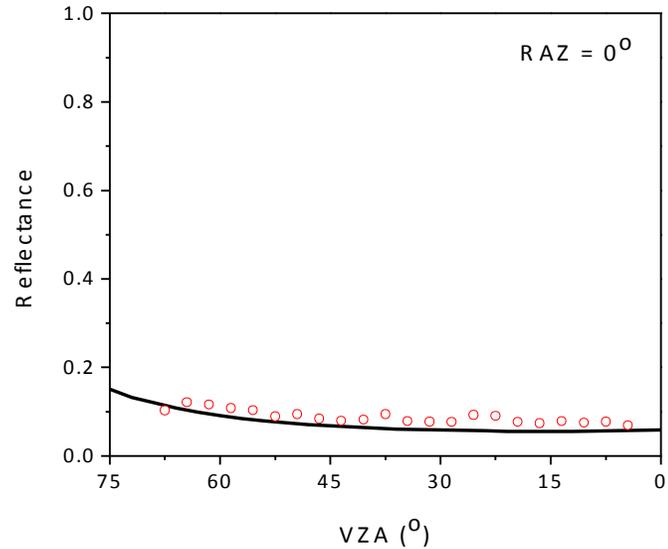
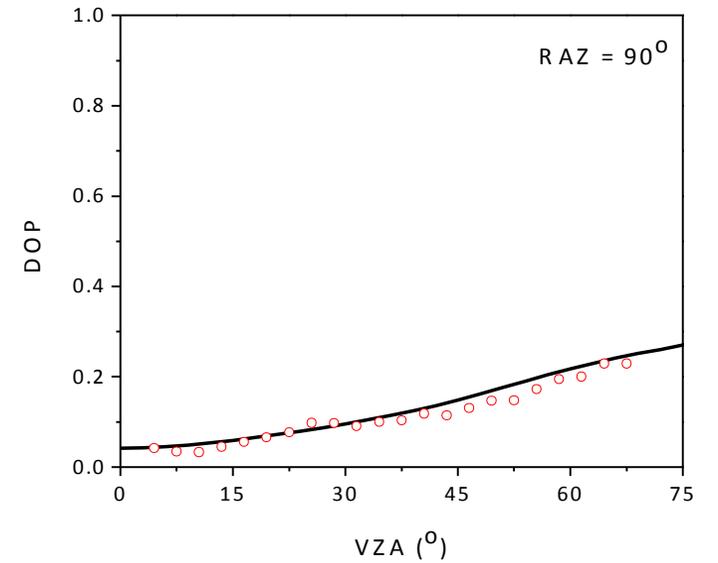
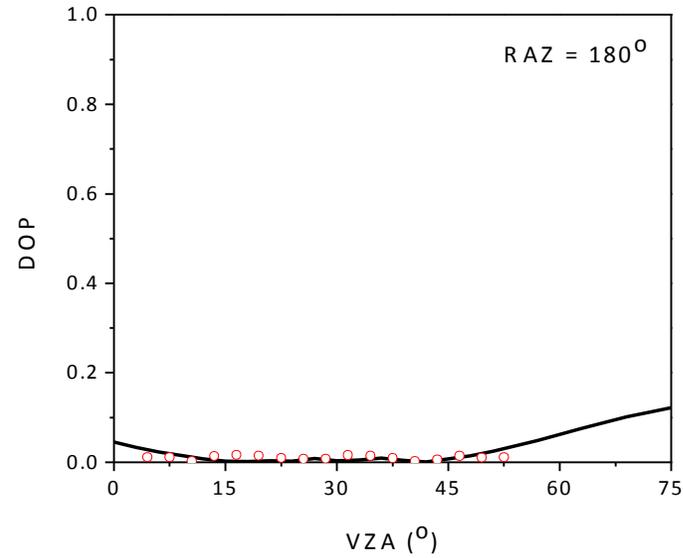
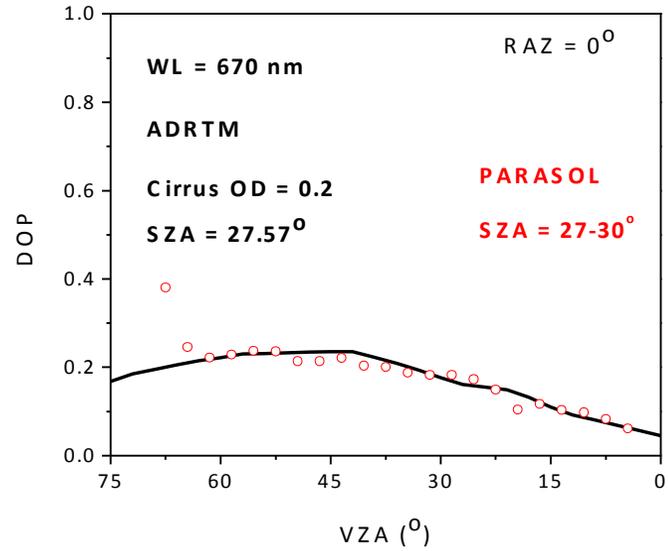
# Comparing model results with satellite data at a wavelength of 490 nm and a SZA of 49.60 deg.

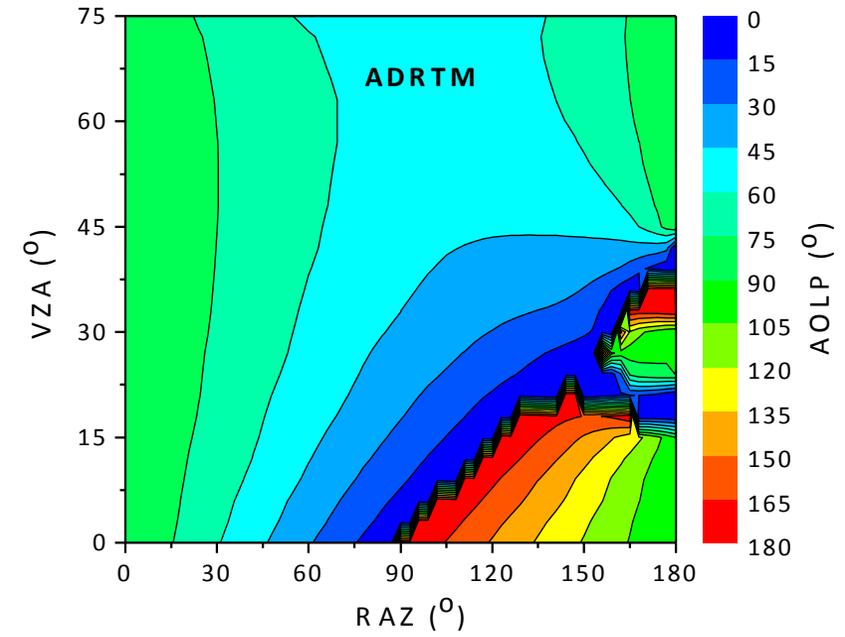
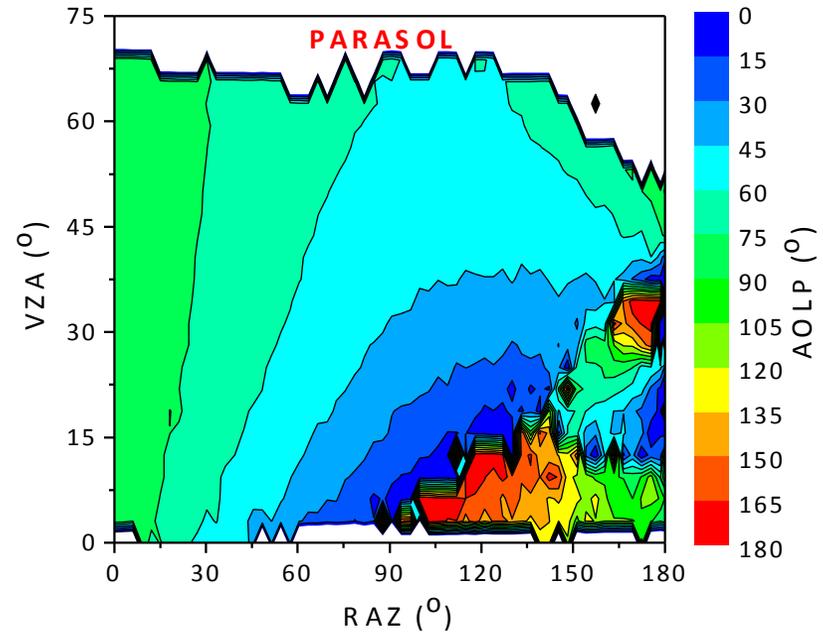


Note: PARASOL equator crossing time is 13:30, thus SZA = 49.60 deg only happens at high latitudes, where super-thin clouds are few. So we set cirrus OD = 0.0 when SZA is large.

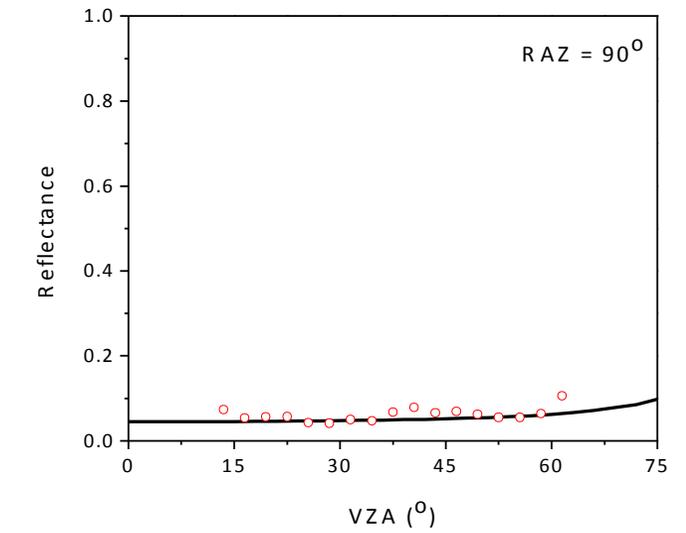
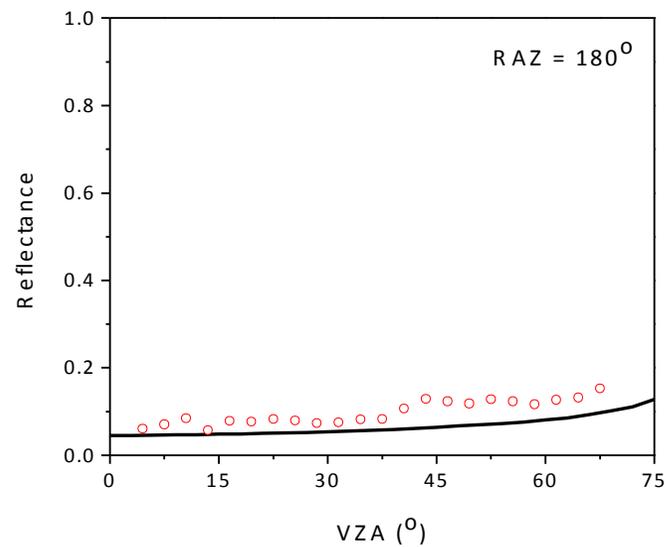
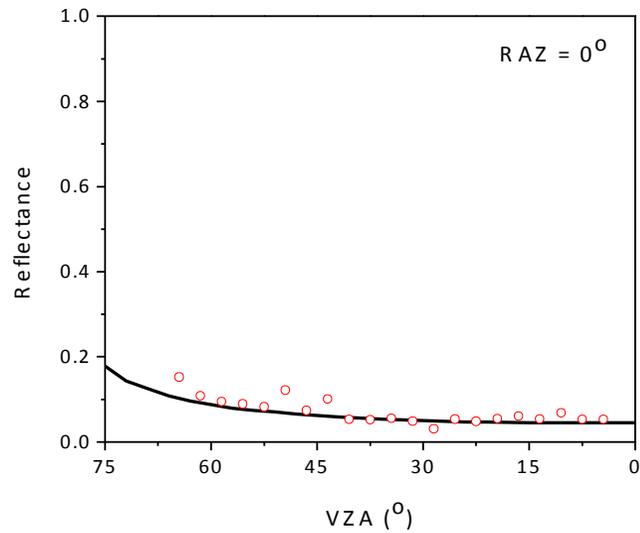
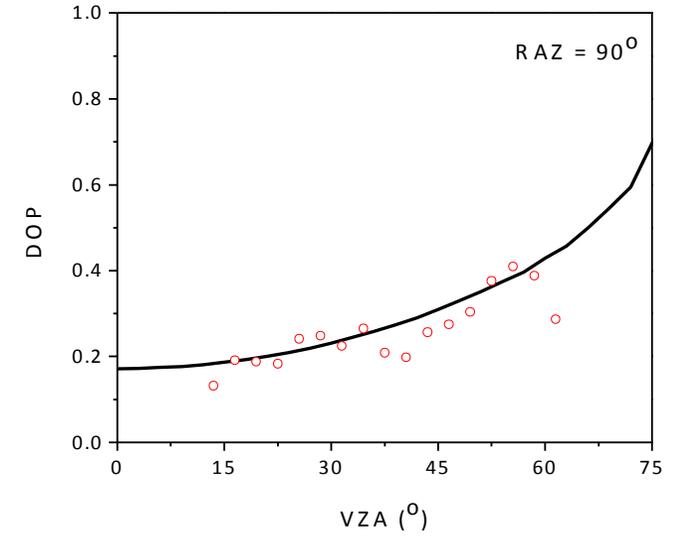
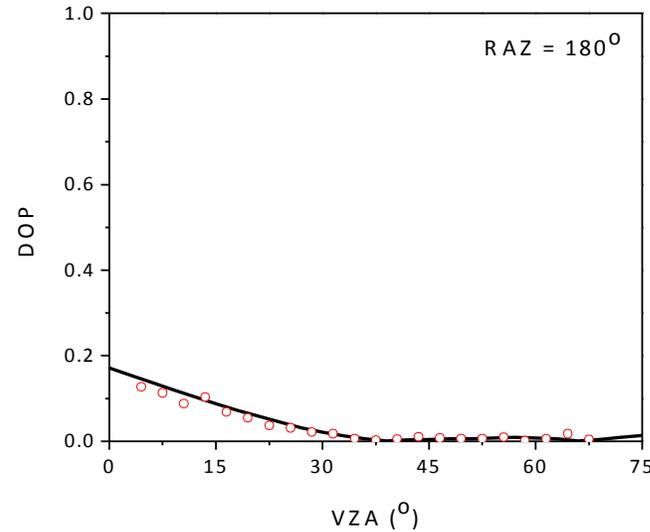
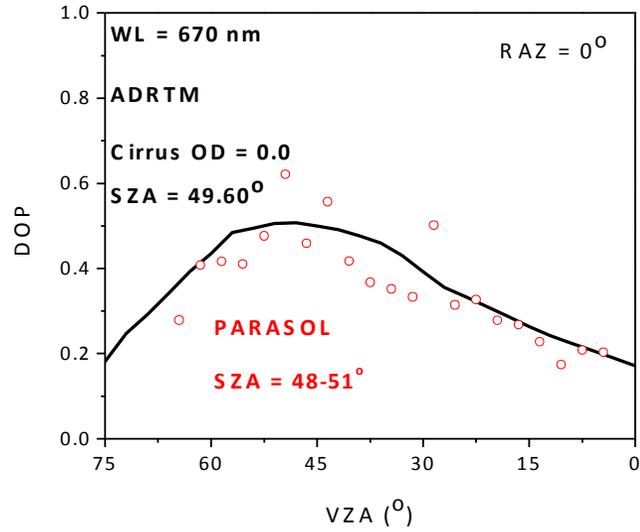


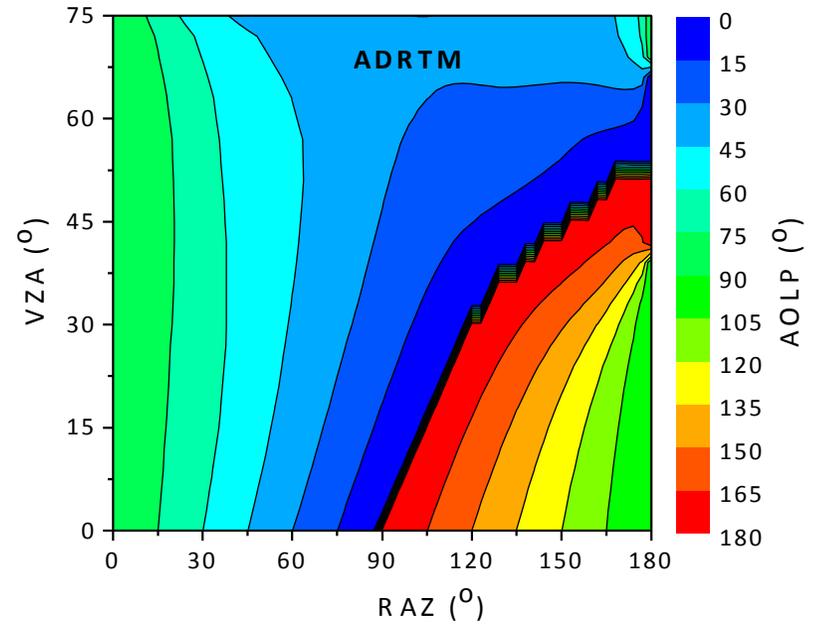
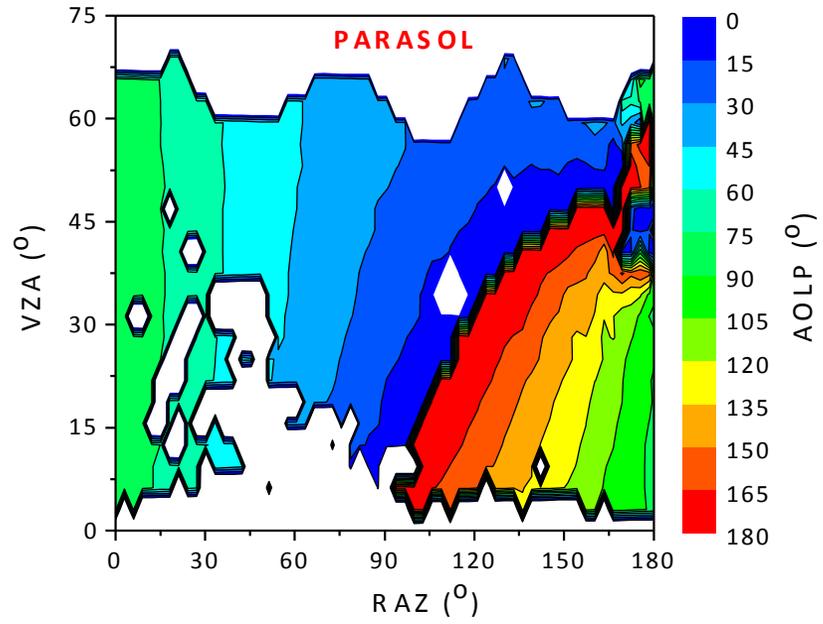
# Comparing model results with satellite data at a wavelength of 670 nm and a SZA of 27.57 deg



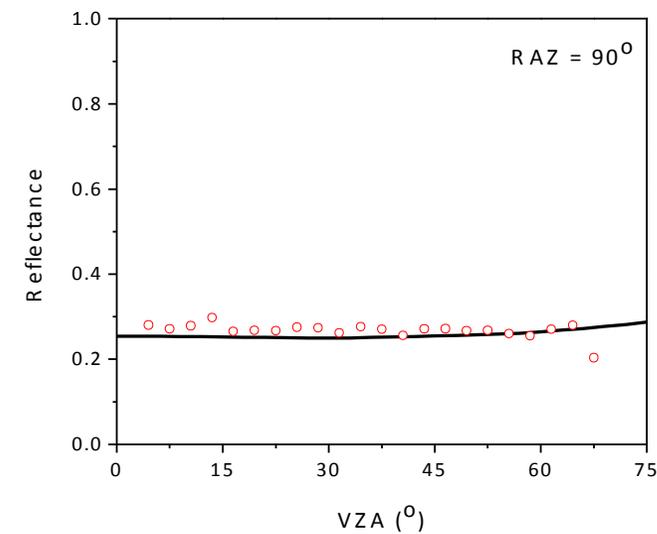
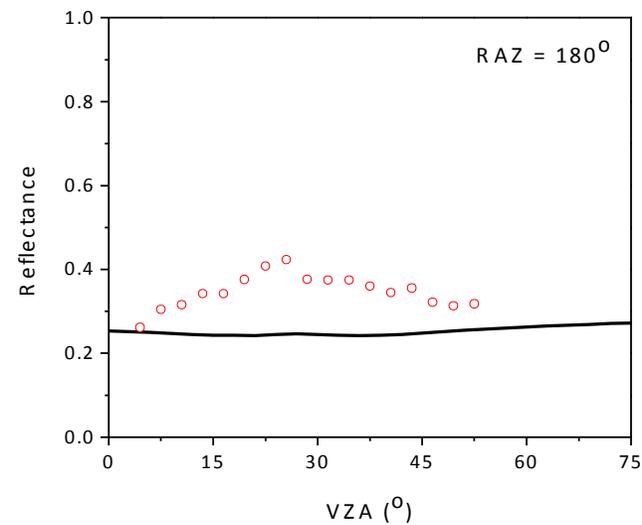
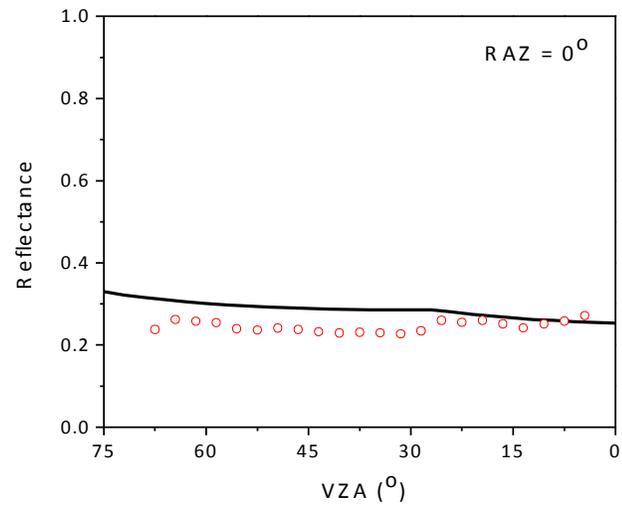
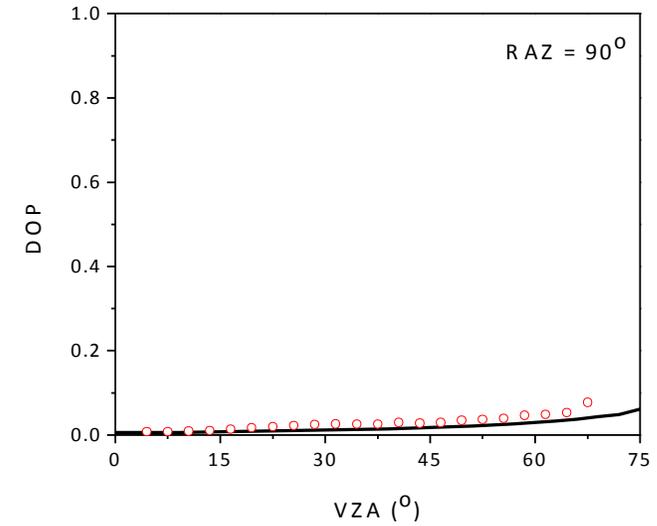
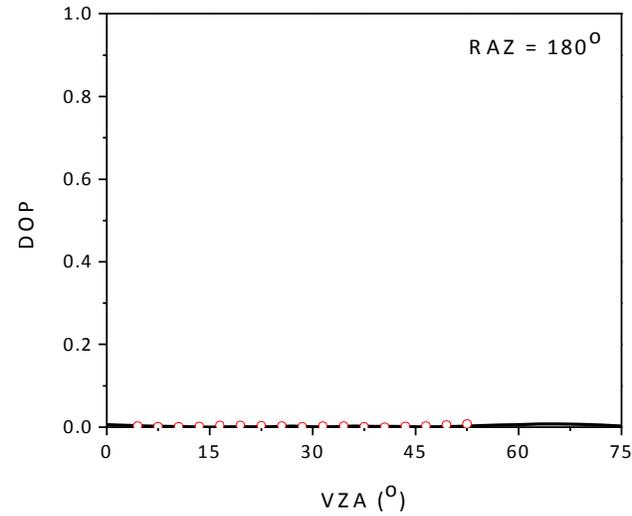
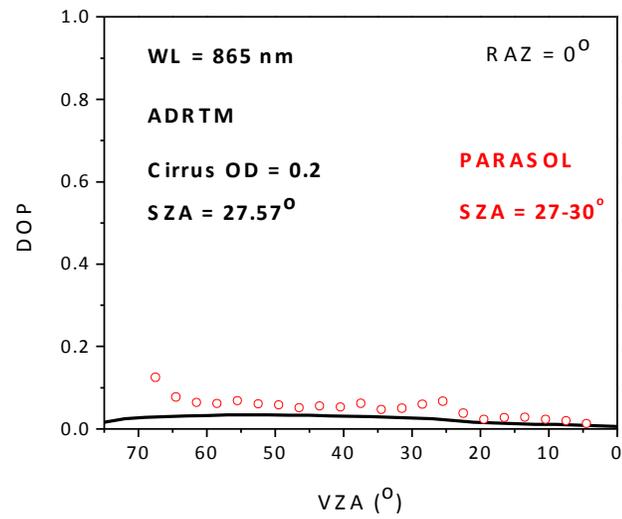


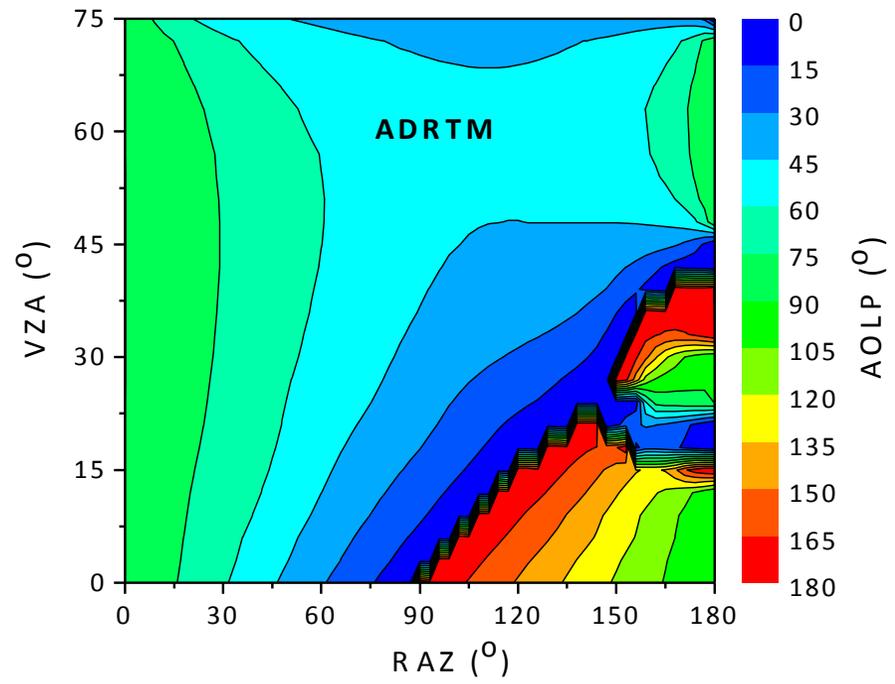
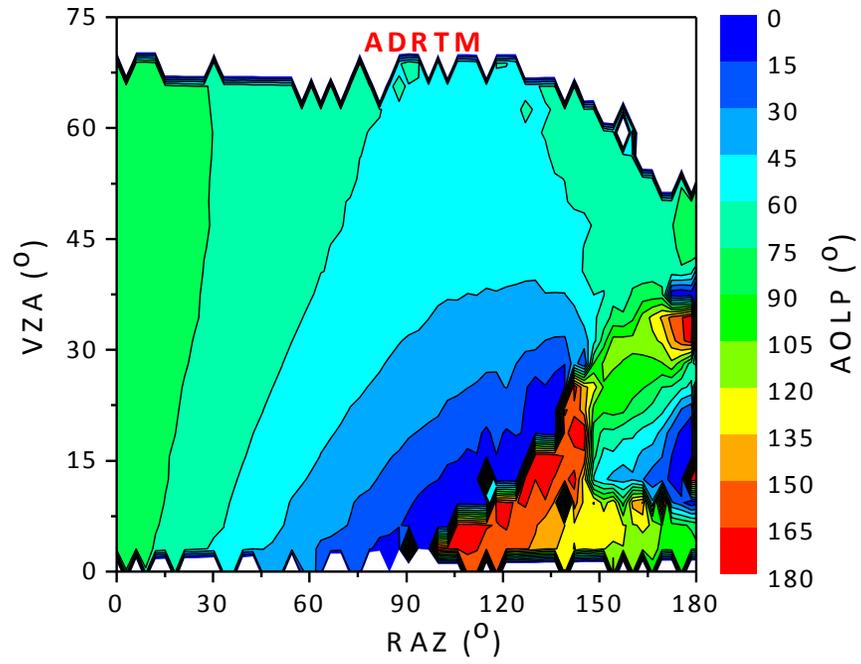
# Comparing model results with satellite data at a wavelength of 670 nm and a SZA of 49.60 deg



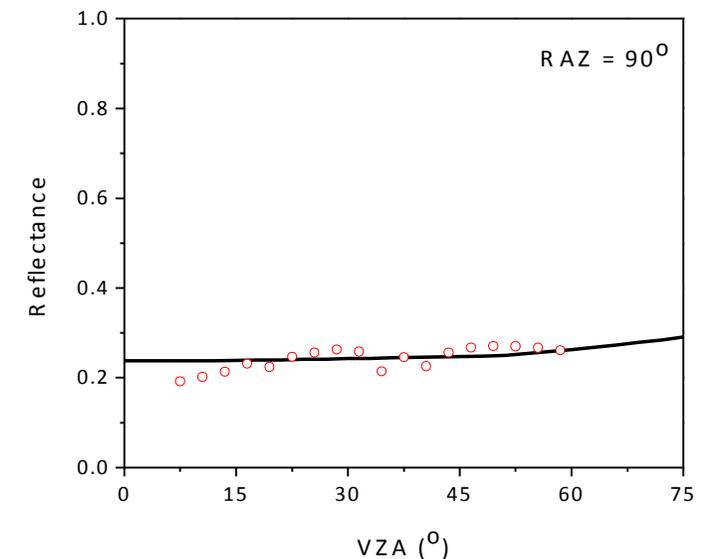
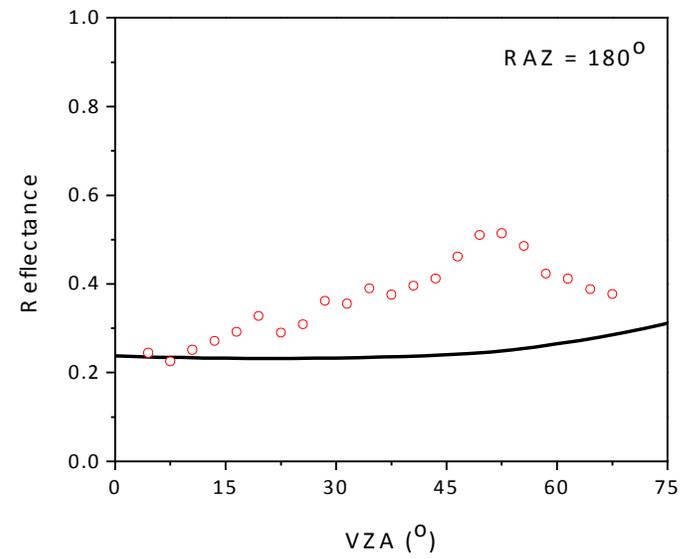
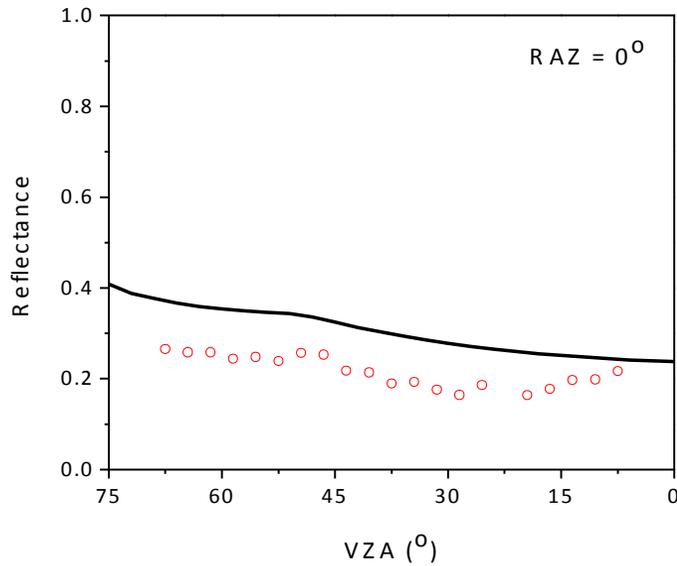
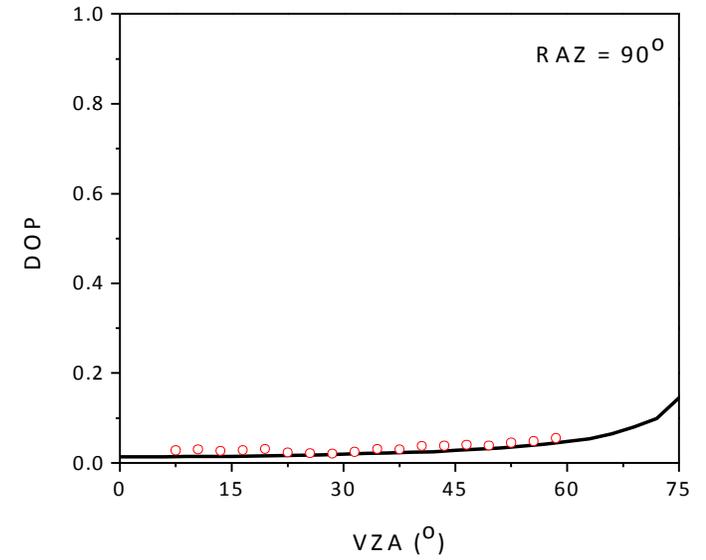
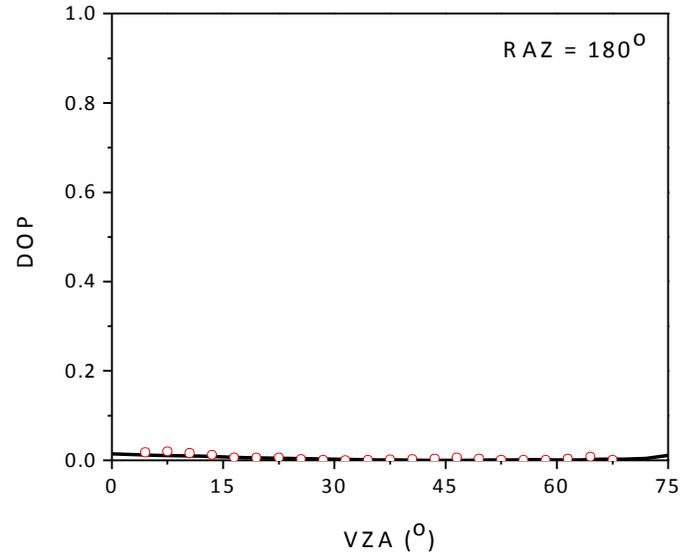
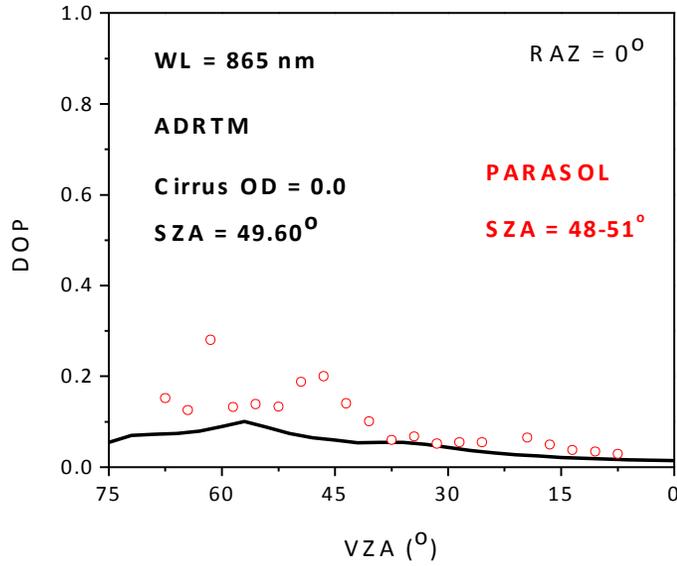


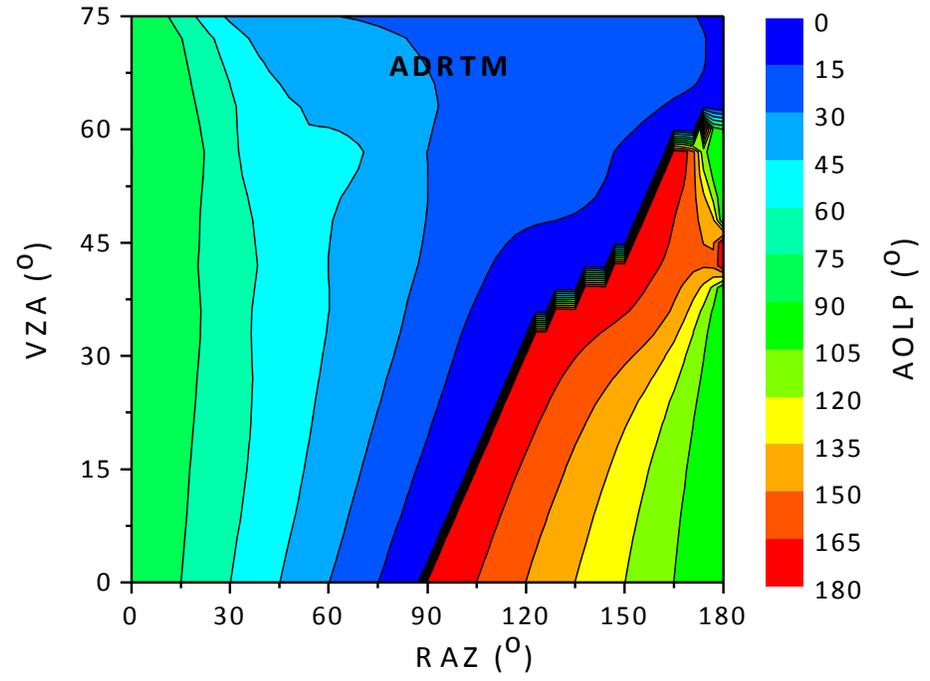
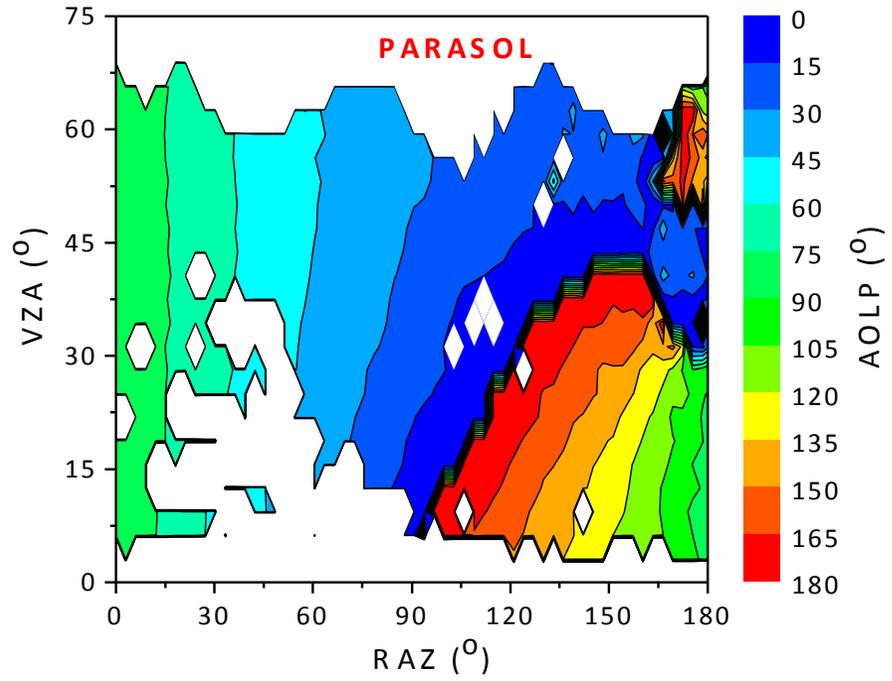
# Comparing model results with satellite data at a wavelength of 865 nm and a SZA of 27.57 deg



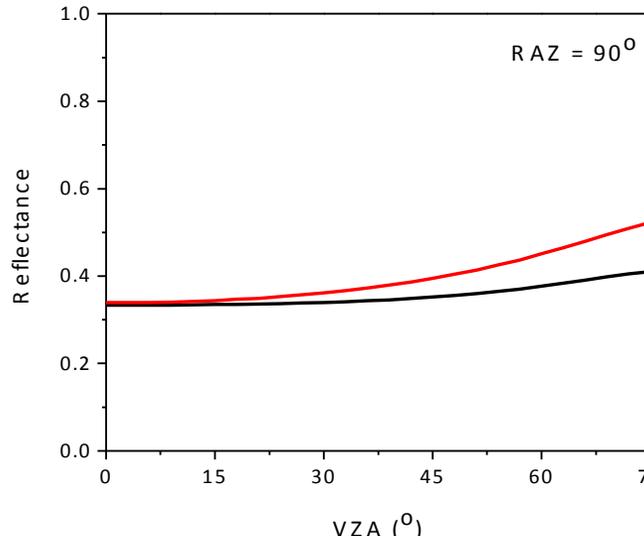
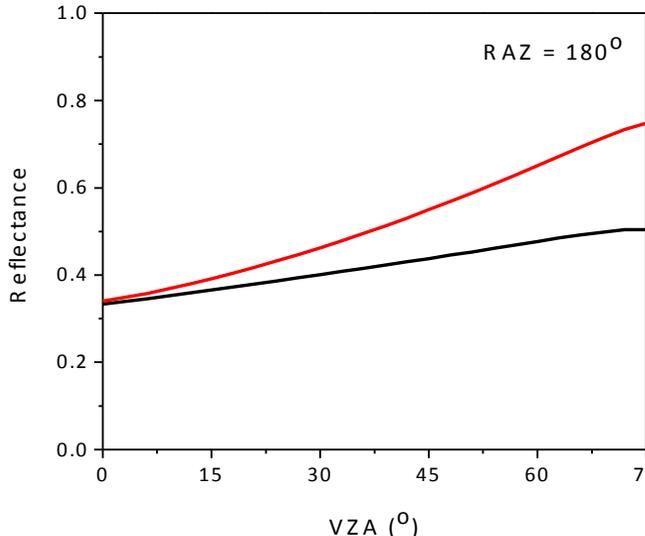
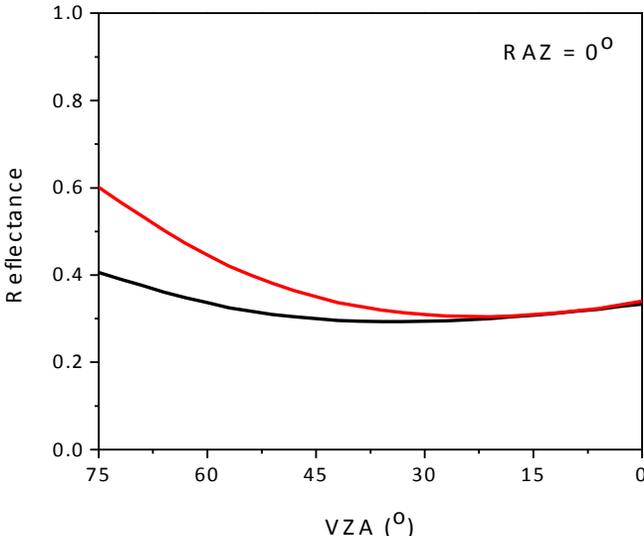
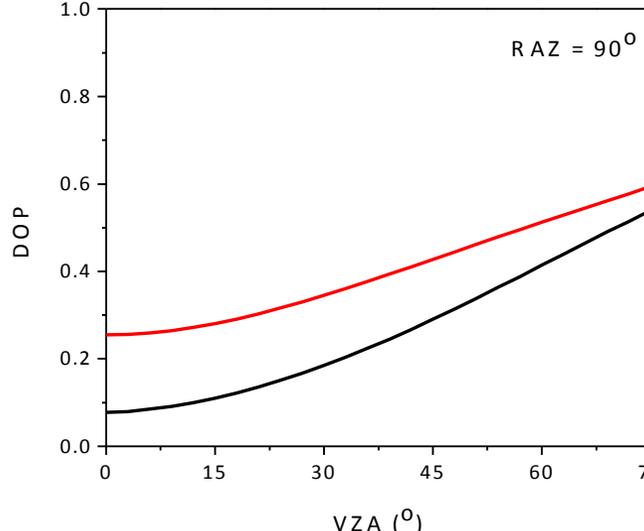
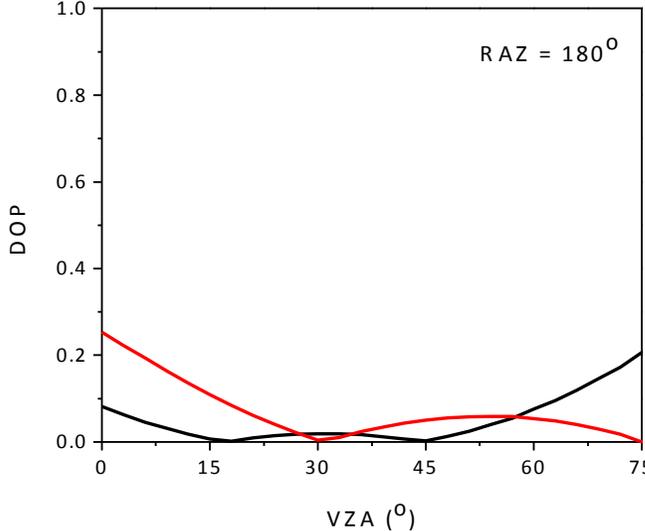
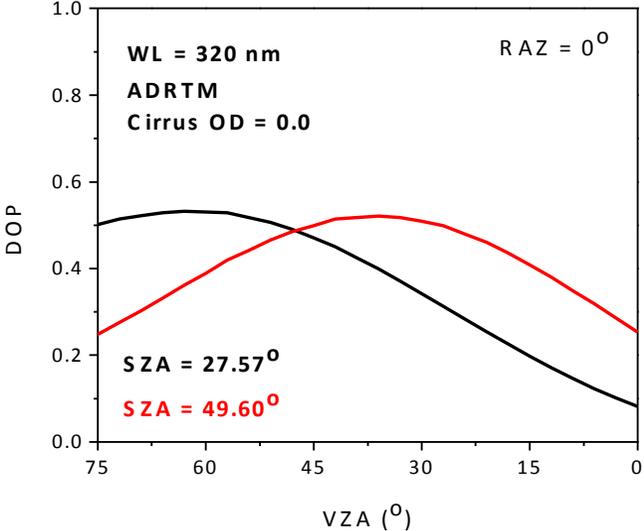


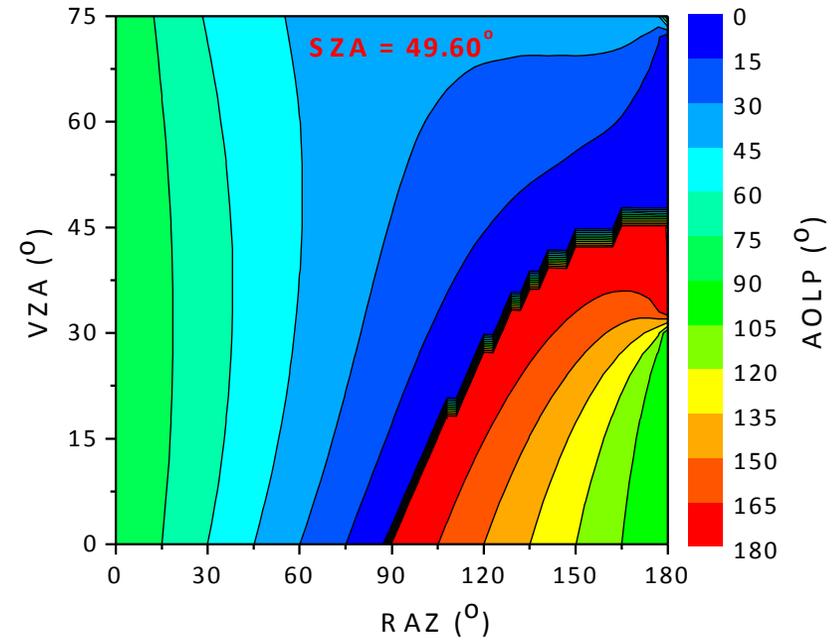
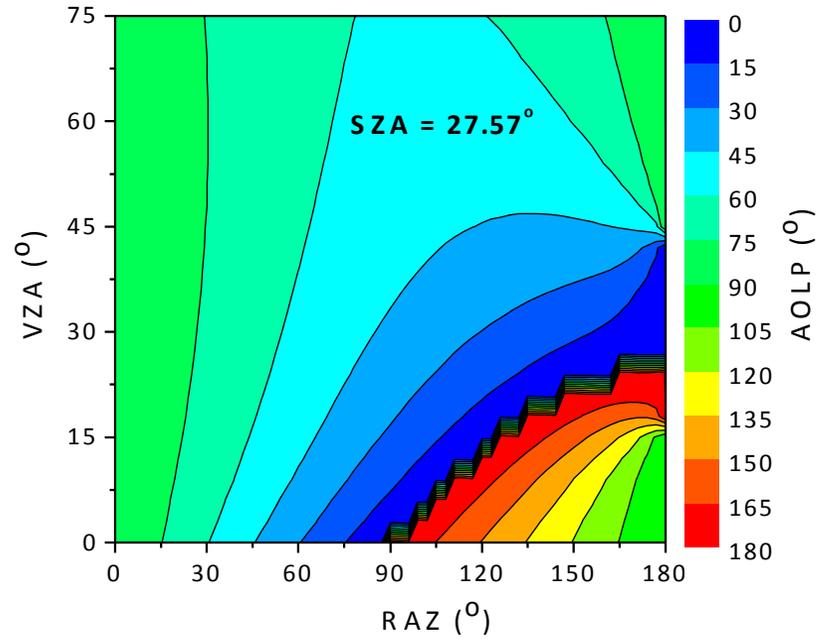
# Comparing model results with satellite data at a wavelength of 865 nm and a SZA of 49.60 deg





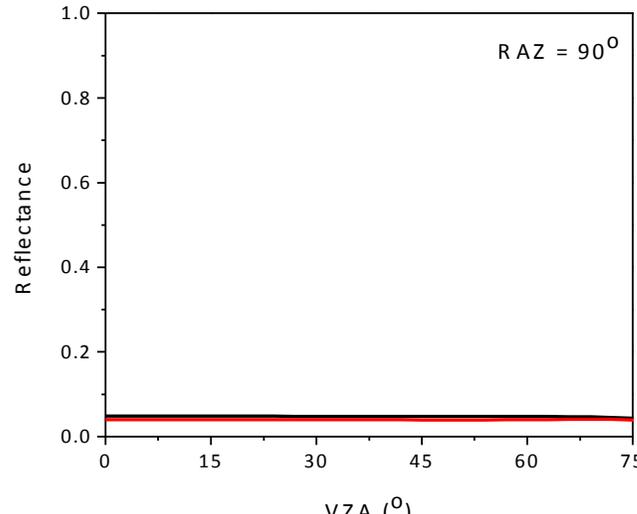
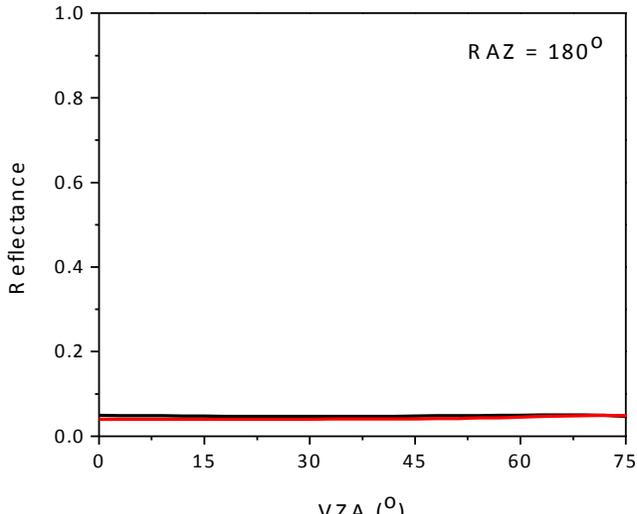
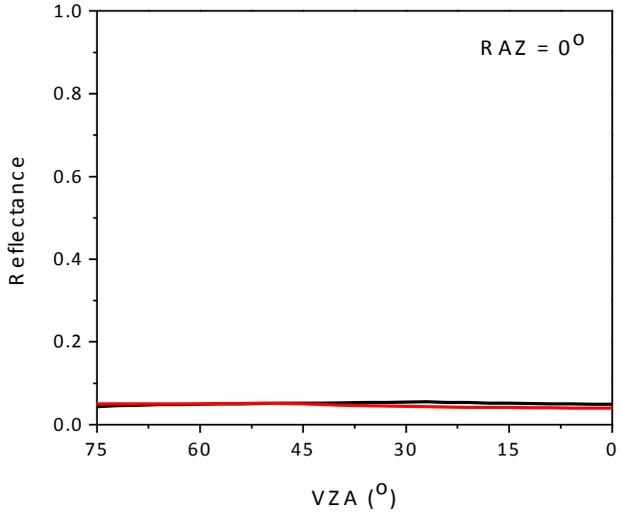
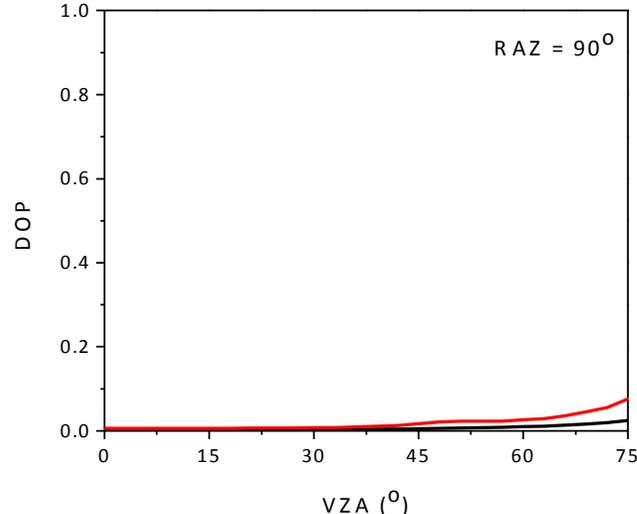
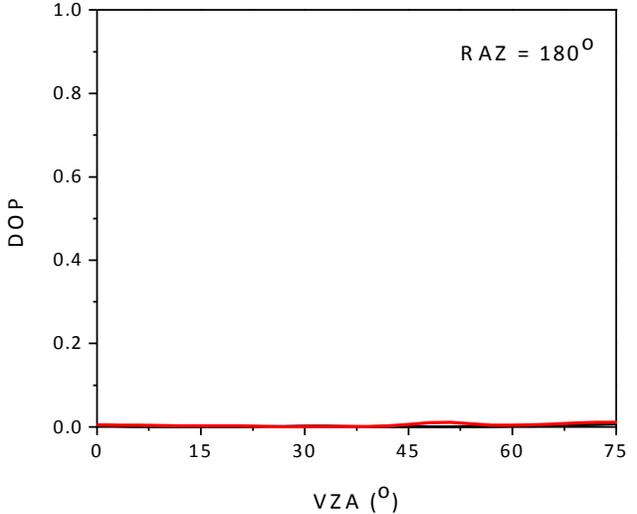
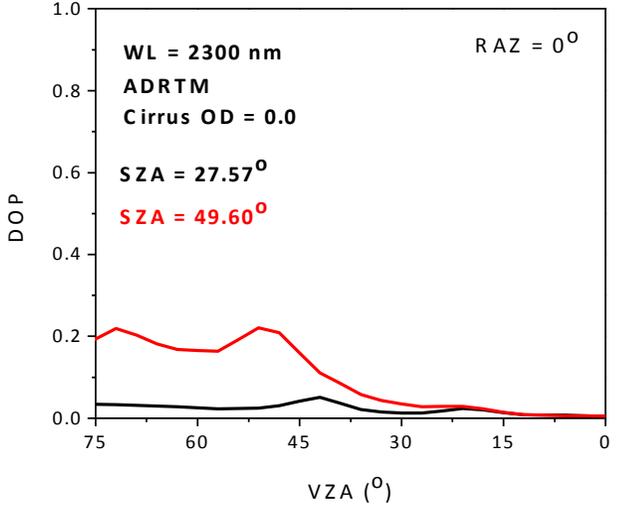
# Model results at a wavelength of 320 nm

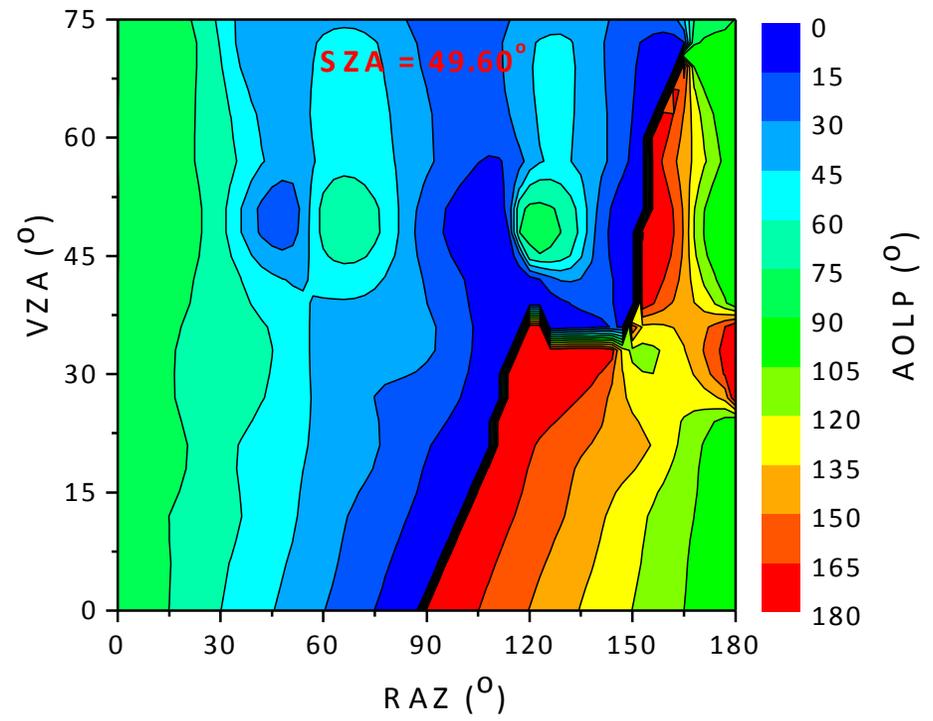
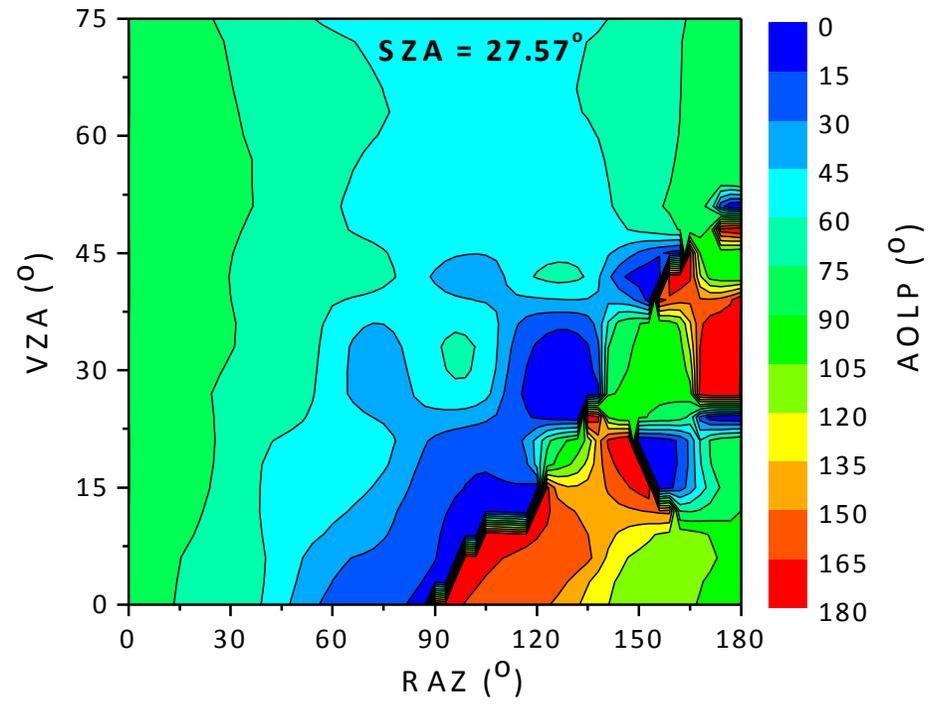






# Model results at a wavelength of 2300 nm







## Summary

1. Polarization states of reflected solar radiation from evergreen broad-leaf trees can be accurately modeled.
2. The PROSAIL leaf optical spectra model is used to obtain the total reflectance.
3. Light polarization is approximated with uppermost leaves' scattering of solar spectra.
4. PARASOL data at 3 wavelengths are used to obtain leaves' fraction and distribution coefficients.

## Next: Deciduous Forest

